Appendix D
Hydrology

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Appendix D
Hydrology

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

HYDROLOGIC PROCESSES

Hydrology, in the context of streambank protection, includes the study of surface water, its movement and changes in the quantity of flow in a channel and over its banks. Surface-water hydrology, influenced by the physical characteristics of the watershed, involves the transport, storage and change in the quality and quantity of water in a stream. These attributes determine the physical character of the stream. The volume of water flowing down a stream and the duration of that flow determines the forces acting on the stream channel and, therefore, a stream's dimensional characteristics (see Appendix F, *Fluvial Geomorphology*). Consequently, all streambank projects must be based on, or take into consideration, hydrology.

Hydrologic processes can be studied on a wide range of scales from the watershed to a site-specific project location. Watershed hydrology involves the study of the size and shape of the drainage basin, including its stream-network pattern, geology, vegetation, soils and other variables that influence the movement and quantity of water flow. Human impacts, such as infrastructure, dams, flood control and irrigation practices also influence the hydrologic regime.

Stream-Flow Characteristics

Stream-Flow Hydrographs (Discharge vs. Time)

One of the tools used to evaluate stream flow at a given location on a stream is a *hydrograph.* This is a graph that tracks the rate of runoff (discharge plotted against time). V.T. Chow[1] describes the hydrograph as "an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff of a particular drainage basin." Discharge is expressed in the hydrograph as volume per unit time; that is, cubic feet per second (cfs) or cubic meters per second (cms). Discharge is plotted on the vertical (ordinate) axis, and time is plotted on the horizontal (abscissa) axis.

Annual hydrographs and storm hydrographs are the two most important types of hydrographs. Annual hydrographs plot stream flow for an entire water year. The total volume of flow tracked on an annual hydrograph is the basin yield. An example of an annual hydrograph is shown in *Figure D-1* on the following page.

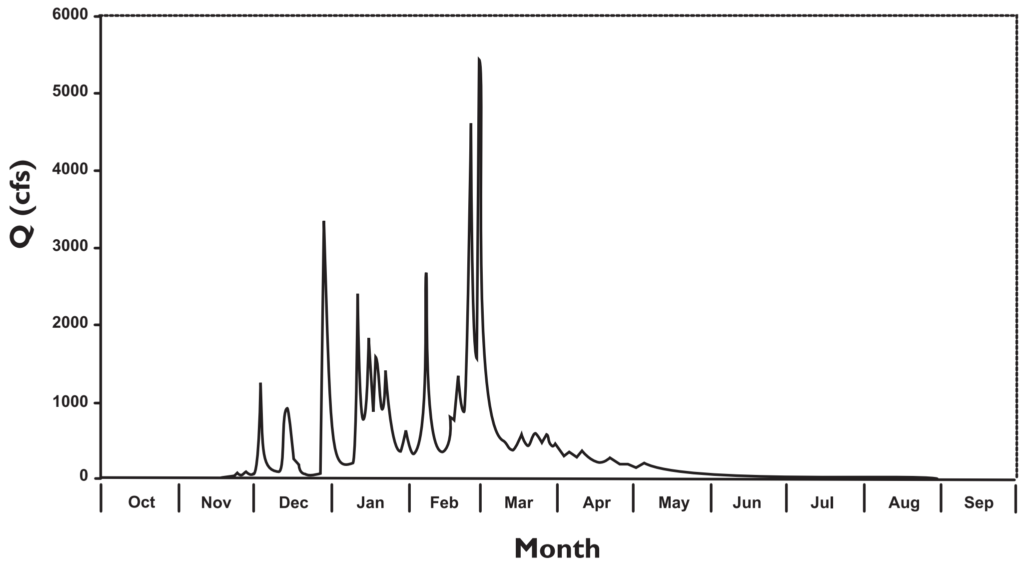

Figure D-1. Hydrograph of a storm-driven stream in western Washington.

A storm hydrograph plots discharge during a single storm event whose time units may be in days or hours. Figure D-2 shows four components of a hydrograph during a storm. The flow volume represented in the curve segment AB is usually called "base flow" – the flow that occurs during periods of no precipitation. A stream's base flow comes from groundwater that has slowly seeped through surface soils until it reaches the channel. Segment BC on the storm hydrograph is the "rising limb," where direct runoff begins at point B, and flow volume peaks at point C. Flow then declines, as represented by Segment CD, ending at D. Segment DE represents the return to a normal base-flow discharge. The "lag to peak" is the time difference from the moment of highest rainfall intensity to the peak runoff rate and is largely dependent on pre-existing moisture conditions and soil-infiltration rates at the drainage area.

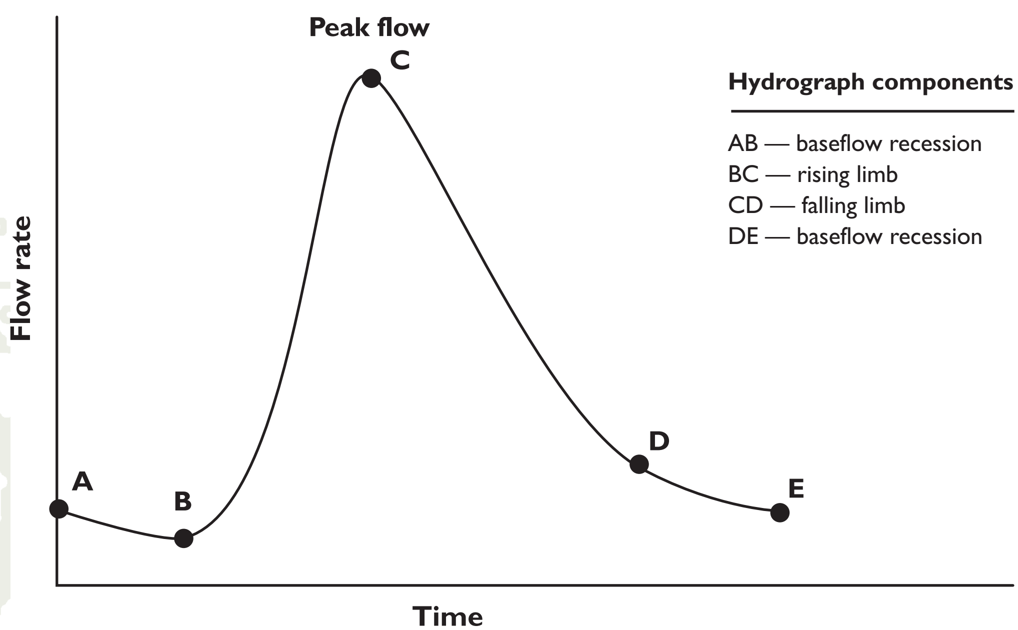

Figure D-2. Storm hydrograph (adapted from Chow, Maidmont and Mays, Applied Hydrology, p. 134, 1988, McGraw Hill)

Storm-Driven Systems

A typical storm-driven system hydrograph from a perennial stream in Washington is shown in *Figure D-3*. A stream that originates from a spring or is fed primarily from groundwater will have a very smooth hydrograph curve, indicative of relatively constant base flow. Discharge may gradually rise and fall in relation to seasonal precipitation patterns and their influence on the groundwater table. The water table recharges or rises in elevation during wet periods and falls or decreases in elevation during drier months. Seasonal changes will register with more clarity on the hydrograph farther downstream in the watershed where tributaries feed into the stream flow and the spring water or groundwater becomes a smaller percentage of total stream-flow volume. In contrast to perennial streams, ephemeral streams have extended dry periods of no surface flow in the channel, followed by intervals of abrupt or flashy discharge caused by seasonal storm events. In this case, rainfall usually becomes direct runoff and reaches the channel as overland flow. Overland flow is a thin layer of water that spreads over a wide surface or slope before it is concentrated or confined to a channel. Overland flow occurs when rainfall intensity of a given storm exceeds the soil-infiltration rate of the basin.

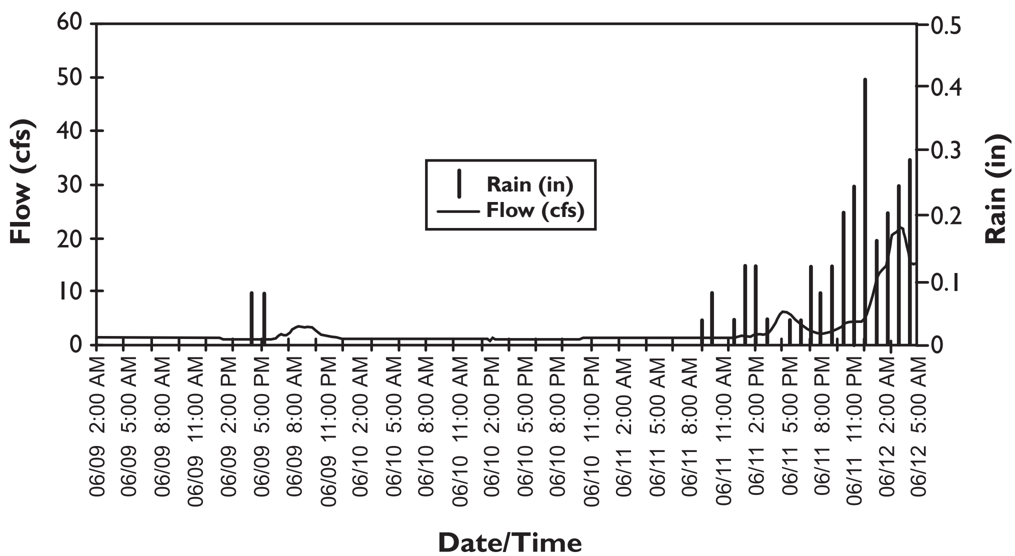

Figure D-3. Storm hydrograph of a perennial stream in western Washington.

Snowmelt-Driven Systems

In regions of the country where the majority of annual precipitation is snow, runoff from snowmelt during spring and early summer comprises the majority of basin yield. A snowmelt-driven system usually creates a smoother curve on a hydrograph (*Figure D-4*) than storm-driven streams (e.g., *Figure D-1*) because a snow pack usually supplies a steady rate of flow. However, a rain-on-snow event, where rain and snowmelt simultaneously contribute to runoff, often produces dramatic spikes in the hydrograph that may correspond with flooding. These events usually occur as a result of the ambient air temperature warming, which causes precipitation to fall as rain rather than snow, with the warmer air also contributing to the melting of the snowpack. The contribution of rain and snowmelt can also coincide with saturated soil conditions, where the ground can no longer absorb or store water, resulting in the direct discharge of overland flow to surface waters. Rain-on-snow events are frequent in the mountainous regions of western Washington and are a common cause of extreme flow conditions and flood events.

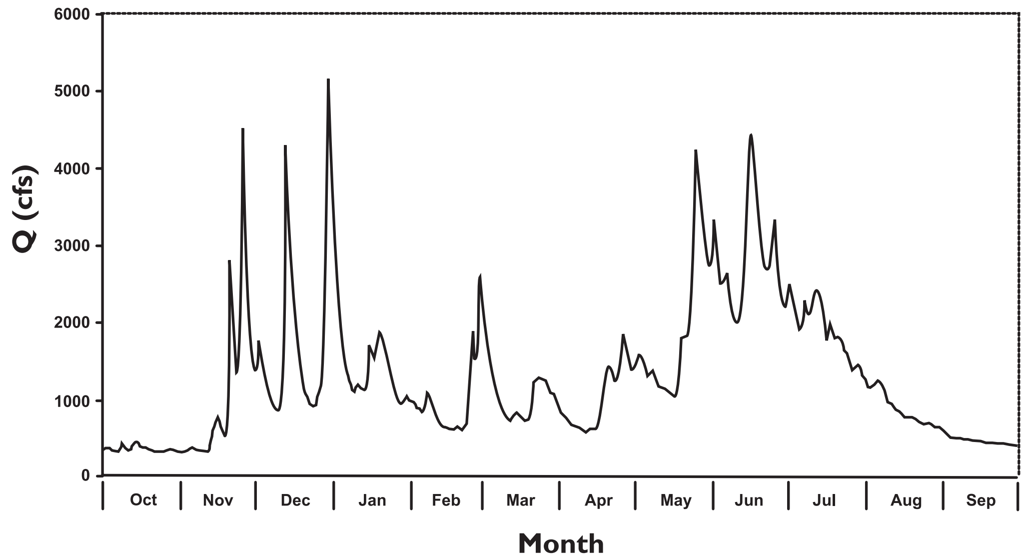

Figure D-4. Storm hydrograph of snowfall-driven stream in eastern Washington.

Gaining and Losing Stream Reaches

Typically, a drainage system's base-flow volume increases in a downstream direction; this may be defined as a *gaining* stream reach and is common throughout Washington wherever groundwater maintains the base flow. A *losing* stream reach occurs where base-flow volume decreases in a downstream direction. Losing steam reaches are most common in arid climates where the loss of water through subsurface infiltration exceeds the rate of flow in the channel. Flow diversions (as discussed in the following sections) may alter base flow and result in loss of stream flow. In some cases, the hydrology of a stream may experience both phenomena, gaining and losing flow volume as the subsurface geology and/or water use changes in the watershed.

Regulated Flow Regimes

There are few major stream drainages that are still undeveloped. Most streams are affected by some form of man-made flow regulation that impounds, diverts, augments and/or modifies their natural hydrologic regime. When examining a historic hydrologic record in a regulated stream, it is often necessary to bracket the data; that is, separate the data based on chronological events of development. For example, separating differences in the flow regime from pre-dam to post-dam hydrologic conditions is necessary to plan and anticipate future conditions. In an urban area, the different flow regimes that may have existed before and after development (e.g., accounting for the influence of impervious ground surface) should also be evaluated.

Reservoirs and Dams

Hydropower

Dams constructed to produce hydroelectric power are common throughout Washington. The effects of dams on the hydrology of a system can be dramatic. Generally, the ability of a dam to store water in a reservoir behind it lowers the magnitude of downstream peak flows. However, the rate at which the dam releases its stored water generally *increases* a river's low flow or base flow from what it was in the pre-dam era. Flows released to generate power through turbines create a sudden increase in discharge downstream from a dam and a corresponding steep rise in the hydrograph, often referred to as "ramping up." Once the demand for power is met, flow volumes are immediately reduced, causing a sharp fall in the curve. This cyclic rise and fall of flow volumes can affect the morphology of the river, change riparian-plant-community distribution and composition, and modify the physical properties of the river system by altering erosional and depositional processes downstream.

Flood Control

Dams, with their ability to store storm runoff and/or snowmelt, protect people and property from the threat of flooding. As discussed in the previous section, dams reduce the volume of peak flows and alter the frequency and duration of flood events. Other flood-control practices that affect hydrology are stream channelization and the construction of levees. Channelization practices reduce the likelihood and duration of a flood by increasing the stream's base- and high-flow velocities. Levees reduce the area of the active floodplain, which also increases the magnitude and frequency of flow in the channel. The faster the flow volume moves through the channel, the less likely the channel is to flood.

Diversions

Seasonal Irrigation Practices

Stream-flow diversions for agricultural use often reduce the overall flow volume of a stream system. Water demands for irrigation are seasonal, depending upon the crop, farming practice and climate in question. Irrigation commonly results in reduced stream flow as water is diverted away from the channel into canals and ditches. This can result in flow reductions and increased water temperatures that may be dangerous to fish.

Water Supply

Another diversion practice involves industrial and municipal water supplies. These types of diversions are used throughout the year and do not result in the seasonal flux that is typical of irrigation diversions. However, during a drought or in the driest months of the year, diversions (in total) may completely dewater a system if instream flow requirements are not identified and maintained.

Flow Augmentation

Flow augmentation is often practiced where the demand for water exceeds the natural supply in a watershed. Augmentations take water from one drainage basin and divert it to another basin, often transporting it through tunnels, aqueducts or open ditches. The discharge is often guided into a natural stream channel or directly into a reservoir. Usually, flow augmentations occur during spring and early summer runoff when water is most abundant and reservoirs are full. Therefore, a watershed system may show a dramatic increase in the magnitude, duration and frequency of peak flows if it is being augmented.

Urban Hydrology

Urbanization of a watershed has a profound impact on stream hydrology. Increased impervious surfaces are a common cause of increased peak-runoff volumes. Examples of impervious surfaces include paved streets and parking lots and roofs. Impervious surfaces decrease soil infiltration rates to zero (see *Figure D-5*[2]). As runoff volumes in urban channels increase (because water is no longer infiltrating the soil), the duration of high flows decreases (because groundwater is no longer contributing to the flow). Also, urban development causes a decrease in lag time between rainfall and runoff by increasing the hydraulic efficiency of the drainage system (water can reach the channel more swiftly when it travels over smooth, hard surfaces). Artificial channels, curbs, gutters and storm sewers increase the magnitude of flood peaks by creating smoother conveyance and decreased storage in the channel and surrounding drainage area.[2] A combination of increased peak-runoff volumes, decreased durations and hydraulic efficiency results in more "erosive work" or hydraulic force acting on a stream channel. On the other hand, when storm flows are captured in detention facilities and gradually released, storm-flow duration increases and peak flow decreases from that of developed conditions.

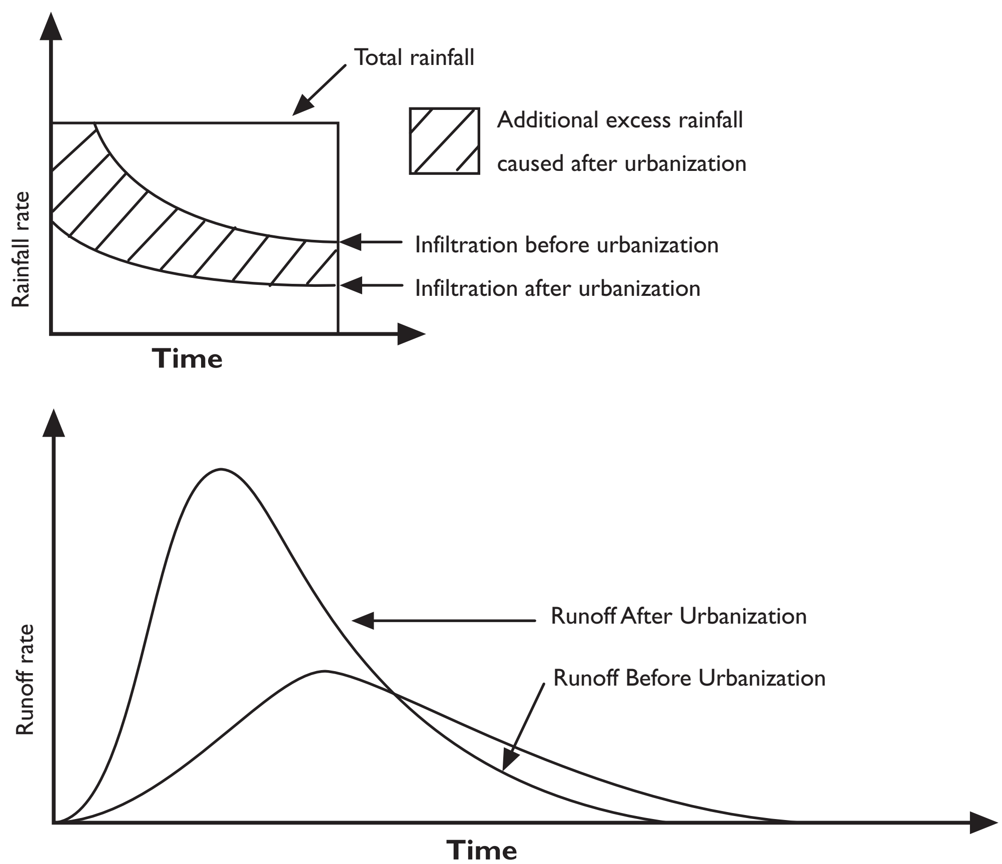

Figure D-5. Urban Hydrograph[2]

The incorporation of storm water detention basins and storm sewers greatly complicates hydrologic analysis. Urban hydrologic modeling is complex and time consuming, but essential to streambank-protection projects. Gauge data and traditional models discussed in the following sections are useful, but inadequate to do the whole job. Urban hydrologic systems often require data collection and modeling that is specific to the urban catchment under consideration.

Urbanization has the most profound impact on streams during the minor floods flows that happen fairly frequently and the least impact on streams during the major floods that happen only rarely. The following provides a general outline for hydrologic analysis of urban settings when implementing a streambank-protection project:

- determine whether the channel has responded to altered hydrology (refer to Appendix F),
- consider potential changes in watershed boundaries due to storm-sewer configurations,
- evaluate flow records with respect to level of urbanization, and
- consider future urbanization trends and possible hydrologic responses.

HYDROLOGIC ANALYSIS

Historic and Current Hydrologic Data

Hydrology at Gauged Stream Sites

The hydrologic statistics described in this section are typically derived from historic stream-gauge data. One must decide if the period of record is long enough to be statistically significant or what portion, if any, of the period of record is relevant. Gauge data usually include mean daily flows for each day. If the project site is in an urbanized or suburbanized basin, it is better to use instantaneous peak flows rather than mean daily flows for deriving statistics. Likewise, only a short period of record is usually relevant in an urban environment because rapid development and changing hydrologic conditions tends to make historic data obsolete. Therefore, segmenting the data set to best represent existing or future conditions may be necessary, but it may also leave only a small amount of relevant data to work with.

- *One-, two-, five-, 10-, 20-, 50- and 100-year flows*. These flows are the annual maximum flows that have an average return interval of the stated number of years. Their probability of occurrence in every year is the inverse of the return interval. The *annual maximum series* consists of all maximum annual flood events. For all statistics less than the 10-year event, a partial-duration series should be employed, which uses all flood peaks greater than some arbitrary base magnitude, usually the smallest number of the annual-maximum series. The recurrence interval derived from a partial-duration series is the average frequency of occurrence between floods of a given size irrespective of their relation to the year, or it is the average time between flows that equal or exceed a given base discharge.[4] For all statistics greater than the 10-year event, use either a partial-duration series or an annual, maximum-data series.
- *Mean annual flow.* This is the mean of all mean annual, daily flows over the period of record.
- *Monthly mean flow*. This is the mean generated by averaging all monthly averages for the period of record. Each month has a characteristic mean flow, which is described by this statistic.
- *Mean monthly minimum.* This is the mean of all monthly minimum flows.
- *Mean monthly maximum*. This is the mean of all monthly maximum flows.

The United States Geological Survey provides the most complete and widely used data for hydrologic analyses. USGS gauging stations are found on almost all major drainage systems and are invaluable sources of data and information. The data for most gauging stations are reported as mean daily flow. In some cases, the instantaneous maximum and minimum daily flow values are also reported. Some gauging stations are no longer in operation, so historic data may often be the best and only hydrologic data available for a particular river system.

Information on where to find hydrologic data for all USGS gauging stations as well as recent and current (real-time) hydrologic conditions for many gauging stations is available from the USGS website. The local or regional USGS office may be able to help obtain more recent data and qualifications of historic data. Other sources of potential hydrologic data are state and local agencies, tribal governments and federal agencies (e.g., U.S. Forest Service, Bureau of Land Management and Bureau of Reclamation).

Hydrology at Ungauged Stream Sites

Where gauge data are determined to be absent, insufficient or of questionable reliability, estimating hydrology can be derived through modeling or analysis of precipitation events using data from other stations in the region. It is important to understand that flow resulting from a given precipitation event does not translate to a stream flow of the same probability. For example, the flow resulting from a 10-year, 24-hour rainstorm is not the same as a 10-year flow event. Be certain that stream-flow statistics are provided, not precipitation data. If alternative statistics are presented, justification for their use should be provided.

Regional analysis for ungauged sites works only if flood-frequency characteristics of the various basins having flood records can be correlated with meteorologic or physiographic parameters. If these parameters are available, floods at ungauged sites can be estimated from the physical geography of the basin. This method assumes that, for a large region, homogeneous meteorologic and physiographic conditions exist, and individual basins in the region have flood-frequency curves of approximately the same slope.[4] If appropriate, regional regression equations can be derived and are often available from the USGS. Common regression variables include:

- basin area,
- mean basin elevation,
- annual rainfall, and
- mean channel width.

Analysis of Hydrologic Data

Interpreting a past record of hydrologic events to determine future probabilities of occurrence is known as "frequency analysis" and is often the basis for planning and designing streambank protection. The method of analysis depends upon the data that is available. If the project site is located within a reach where a record of floods exists, the data can be used directly. In the absence of a flood record, other data from neighboring stations can be regionalized and applied to the prediction of floods at the ungauged site.[3] Hydrologic analysis must derive the correct statistics of probability (described as return intervals) and/or flow duration. The references listed at the end of this appendix provide a more detailed and comprehensive methodology for statistical analyses of hydrologic data.

The most commonly applied hydrologic statistics for streambank-protection design are the following:

- *Return Intervals* - the average interval between events equaling or exceeding a given magnitude, and
- *Exceedence Probabilities* - the chance that the annual maximum event of any year will equal or exceed some given value. These values are derived from calculating and plotting a flow-duration curve. Probabilities are the inverse values of return intervals.

Flood-Frequency Analysis

Design criteria for streambank-protection projects will include hydrologic events (often referred to as an x-year flood, such as a 100-year flood) as descriptors. One common method to calculate the probability of a given flow is the Weibell Plotting Position[2]:

$$T = \frac{n + 1}{m}$$

Where: **T** = return interval (years);
n = *number of years of record; and*
m = *rank (number value).*

For example, a certain water elevation for revegetating a streambank may be required for a certain number of days during the critical growing season when the plants must have sufficient soil moisture to establish themselves. To design for this criterion, the amount of flow that can be expected in the stream during this season must be known (perhaps a 0.5-year flow or a three-month average). Determination of the hydrologic regime must be completed prior to any design. Typically, other design criteria for mitigation and habitat design projects will depend upon the hydrologic values derived.

The next section provides a summary of hydrologic characteristics that must be identified as part of a streambank-protection project. If any of these characteristics don't apply or are impossible to determine given available data, it is important to demonstrate why, and then describe how the design criteria can be met without an understanding of these characteristics.

Flow Duration

In addition to the statistics above, one should consider whether or not the project requires an analysis of flow duration. Flow duration refers to the minimum or maximum number of days or hours that a given flow is exceeded for a given time period. Flow-duration statistics must be tailored to the specific nature of the project proposed. Generally, any project whose stated objectives include habitat components designed to sustain a specified life stage should be based on flow-duration statistics. However, flow-duration statistics can only be generated if gauge data are available. Additionally, flow-duration statistics should be based on data specific to the season for which the design is relevant. Note that USGS-derived flow-duration statistics are not applicable, as they are generally not seasonally specific. For example, if a design objective is to sustain sufficient flows for spawning, duration statistics should be based only on those daily-flow data collected during the time of spawning. Hydrologic analysis must include a discussion of what flow-duration data are relevant, whether or not there are sufficient data to derive flow-duration statistics and how they will be derived and applied. For further information regarding derivation of flow-duration statistics, refer to Dunne and Leopold's book, *Water in Environmental Planning*.[3]

Stage-Discharge Relation (Rating Curves)

In hydrology, the term, "stage" refers to the elevation of the water surface above some arbitrary datum. Stage is recorded at gauging stations by measuring water-surface elevations. Stage-discharge relationships are records of stage as a function of time.[4] The stage-discharge graph is called a "rating curve." A rating curve can be helpful in establishing design parameters for a project, such as where and how a given discharge will correspond with a physical attribute of the channel (e.g., an inset, low-flow channel or the bankfull stage).

Single-Event, Rainfall-Simulation Models

The temporal and spatial variations of precipitation, hydrologic abstractions and runoff form the basis of simulation models. Single-event rainfall models are designed to evaluate direct runoff by simulating individual rainfall-runoff events with an emphasis on infiltration rates and surface runoff.[5] Examples of these models include:

- the U.S. Army Corps of Engineers, HEC-1 model;[6]
- the U.S. Natural Resources Soil Conservation Service, Project Formulation-Hydrology model (Technical Release No. 20);[7] and
- the Environmental Protection Agency's Storm Water Management Model.[8]

These models simulate flood events in watersheds and river basins with no provision for pre-existing soil-moisture conditions, and simulations are limited to a single-storm event.[5]

HEC-1 develops a series of interconnected subbasins with hydrologic and hydraulic components. Components may be surface runoff, a stream channel or a reservoir. HEC-1 calculates discharge only, but stage can be indirectly calculated from user input. The result of the model is a computation of stream-flow hydrographs at the targeted location within the watershed.[5]

The objective of Technical Release 20 is to provide the user with a hydrologic analysis of flood events. This model is best applied to watersheds where peak flows are generated by thunderstorms or other high-intensity, short-duration storms. It may be used with as many as nine different rainstorm distributions over a basin with a range of land-use conditions, including various structures that interfere with floodwater conveyance, diversions and channel work.[5]

The EPA's Storm Water Management Model was originally designed for modeling urban storm water runoff and combined sewer overflow. It gives the user many options based on a description of spatial and temporal effects, including storage and/or treatment, cost estimates, and it predicts water quality and quantity values.[5]

Stream-Flow Simulation Models

Stream-flow simulation models are based on continuous stream flow within a watershed and its channels. The Hydrological Simulation Program - FORTRAN is a comprehensive package for the simulation of watershed hydrology and water quality. HSPF uses watershed-scale models for a basin-scale analysis on one-dimensional stream channels. HSPF has been commonly used to simulate hydrology in many watersheds throughout Washington. The Stanford Watershed Model serves as the basis for HSPF. It is comprised of several components, including input data such as precipitation and potential evapotranspiration. If stream flow is influenced by snowmelt, additional meteorological data are necessary. To perform calculations with the Stanford Watershed Model, known or assumed initial conditions are incorporated into the model until the time series input data are exhausted.[5] The model considers four storage zones for precipitation:

1. upper-zone storage,
2. lower-zone storage,
3. groundwater, and
4. snowpack.

Overland flow, infiltration, interflow, base flow and flow-to-groundwater storage are routed within the upper and lower zones to the watershed outlet, where discharge can be expressed as a continuous out-flow hydrograph. To apply the Stanford Watershed Model, typically three to six years of rainfall-runoff data are necessary to calibrate the various parameters, and adjustments are made until an acceptable level of agreement between simulated and recorded flows is established.[2]

HYDROLOGIC DESIGN

Hydrologic design is an integrated process that determines how hydrologic events will affect the physical components of a project. Hydrologic design is a necessary analysis for any streambank-protection project. The level of engineering and choice of structural and geotechnical materials is often based on the hydrologic regime. Hydrologic design must incorporate a much broader scope when a project may affect public safety, infrastructure, aesthetics, economics and natural stream processes.

Flow Types

Distinct flow types and durations that perform different geomorphic and biological functions result from a varying seasonal climate. The following terms are commonly used to describe flow types and are based on a river stage and its relation to physical boundaries and conditions within the channel and floodplain environment:

- low flow,
- flood flow,
- dominant discharge, and
- flow resistance.

Low Flow

A low-flow channel is often formed by base flow and may have the greatest frequency and longest flow duration. The low-flow channel is an inset to a larger, active channel and may be broken down into smaller segments with distinct geomorphic features such as riffles and pools. The stage in the low-flow channel is important to examine if the project's goals include specific revegetation and/or habitat requirements. For example, designing an adequate water depth and velocity is will be critical to the survival of fish species. Likewise, the survival of riparian plant communities and other deep-rooted species may be an integral part of a streambank-protection project that uses a range of bioengineered treatments. Vegetation needs to be planted at a proper bank elevation to make use of moist soil conditions in the low-flow channel for establishment and survival. The best, nonstatistical approximation of this value in Washington is the ordinary high water mark, which is the flow that exists when the water-surface elevation is equal to the elevation of perennial vegetation. This flow level can be determined using Manning's equation[1] or by hydraulic analysis of a surveyed cross section. (Manning's equation is explained later in this appendix under *Flow Resistance and Manning's Equation.*)

Flood Flow

Flood flows are those that exceed the capacity of the channel. Flood stage occurs when water overtops the channel banks to the floodplain surface. Incised channels, however, may contain flood-level flows. Ten-year, 50-year, and 100-year flows are common flood flows used in streambank designs. In ungauged basins, various hydrologic models or regional regression equations may be used to derive flood flows.

Dominant Discharge

Dominant discharge is the flow that produces the greatest morphological effects over an extended period of time. Conceptually, a dominant flow helps describe the flow type that controls the overall shape and function of the active channel. Consequently, dominant discharge should be used as the basis for design of channel characteristics in streambank-protection projects. However, because dominant discharge is difficult to quantify, there are two alternative flows that are commonly used as substitutes:

1. effective discharge (the discharge that transports the most bed load; it can be quantified with knowledge of the channel sediment budget and closely approximates dominant discharge); and
2. bankfull flow.

Bankfull flow is the flow that fills the channel to the top of its banks and at a point where the water begins to overflow onto the floodplain. It generally approximates the dominant discharge only in streams whose hydrology and sediment supply have not been impacted and whose channels have not been impacted by people. In such relatively pristine streams, bankfull flow can be determined from measured cross sections using Manning's equation. Some channels, however, do not have distinct banks; thus, it is hard to determine floodplain-channel boundaries critical to defining bankfull conditions. In channels that are incised or are otherwise impacted, apparent bankfull flow may significantly exceed the dominant discharge and will, therefore, be inappropriate as a design discharge.

Flow Resistance and Manning's Equation

When designing a streambank-protection project using Manning's equation, it is important to consider the relation of channel roughness to discharge. Roughness in a channel, represented by *n* in Manning's equation, refers to all those factors that increase flow resistance, including bed substrate, bank vegetation and relative channel dimensions. Manning's equation expresses the relationship of several variables that include the discharge (Q), hydraulic radius (R_h), velocity (V), the channel slope (S), cross-sectional area of flow (A) and a roughness co-efficient (n).[1] Selection of a roughness coefficient, *n*, will greatly affect the product of the equation. Manning's Equation, in terms of flow depth as it varies with flow rate Q, is expressed as:

$$Q=\frac{1.49S^{1/2}AR_h^{\ 2/3}}{n}=VA$$

Roughness values (*n*) for stream channels can be approximated from reference sources such as those developed by H. H. Barnes, Jr.,[5] D. M. Hicks and P. D. Mason.[9]

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